Design for Biosecurity

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Lecture 14

Sauerbrey Equation and QCM-D

Welcome back to our discussion. We are now in the third week, and today, we'll delve into the fundamentals of mass sensitivity in QCM (Quartz Crystal Microbalance). To begin, let's explore how changes in mass influence frequency. On the y-axis, we have frequency change, and here, we see the basic crystal setup.

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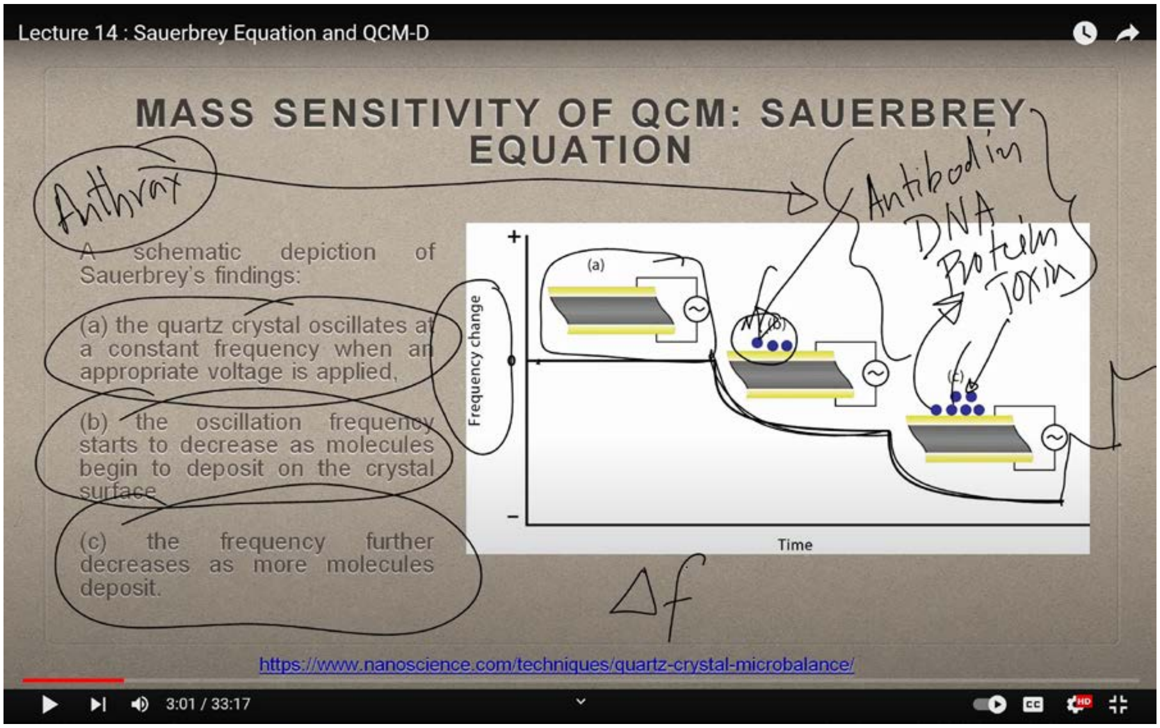

Lecture 14 : Sauerbrey Equation and QCM-D

MASS SENSITIVITY OF QCM: SAUERBREY EQUATION

A schematic depiction of Sauerbrey's findings:

(a) the quartz crystal oscillates at a constant frequency when an appropriate voltage is applied,

(b) the oscillation frequency starts to decrease as molecules begin to deposit on the crystal surface

(c) the frequency further decreases as more molecules deposit.

https://www.nanoscience.com/techniques/quartz-crystal-microbalance/

When molecules are added to the surface of the crystal, a noticeable change occurs. Initially, the crystal oscillates at a certain frequency. However, as soon as these molecules are introduced, the frequency decreases. You can observe this in the graph, the frequency drops as molecules are added. If we continue to add more molecules, the frequency decreases even further, a trend clearly visible as the curve descends.

Now, let's consider what happens when you remove some of these molecules. The frequency begins to increase. As you remove more molecules, the frequency rises further. This process allows us to directly observe the addition and subtraction of mass in real time.

The quartz crystal oscillator, when subjected to a constant voltage, oscillates at a consistent frequency. However, as molecules begin to deposit on the crystal's surface, this frequency starts to decrease. The more molecules that accumulate, the greater the decrease in frequency. For instance, if we replace these molecules with antibodies, proteins, or anthrax toxins, this system becomes a highly sensitive tool capable of detecting changes in the frequency domain.

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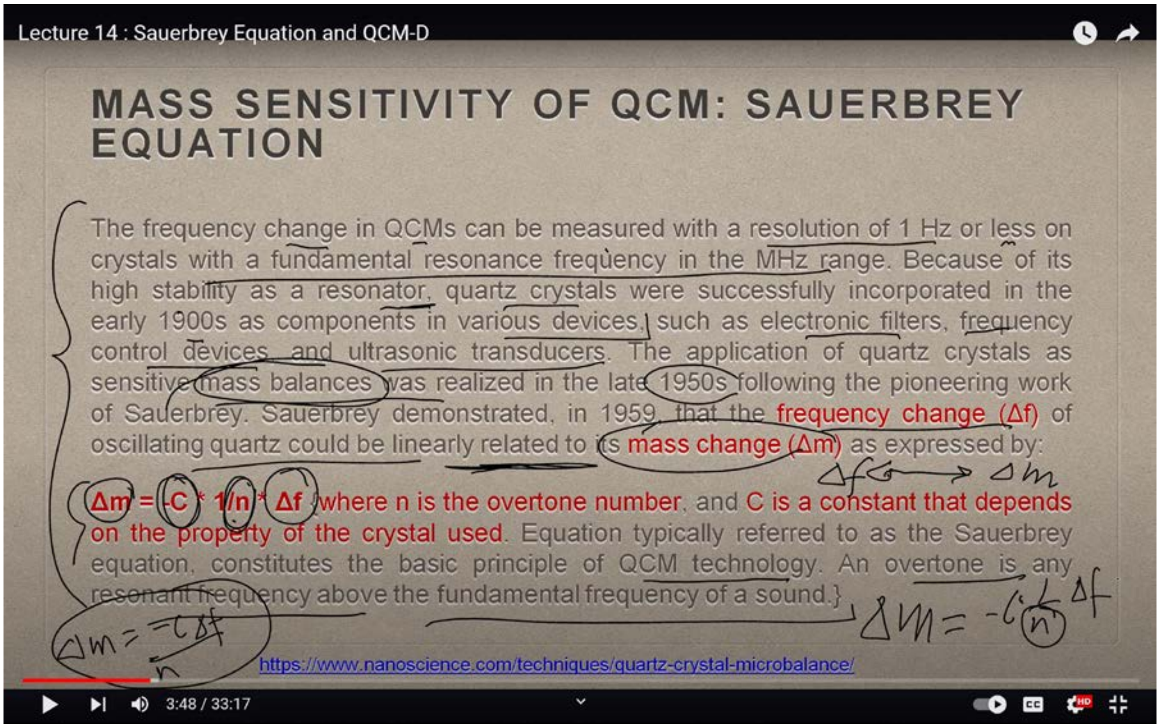

MASS SENSITIVITY OF QCM: SAUERBREY EQUATION

The frequency change in QCMs can be measured with a resolution of 1 Hz or less on crystals with a fundamental resonance frequency in the MHz range. Because of its high stability as a resonator, quartz crystals were successfully incorporated in the early 1900s as components in various devices, such as electronic filters, frequency control devices, and ultrasonic transducers. The application of quartz crystals as sensitive mass balances was realized in the late 1950s following the pioneering work of Sauerbrey. Sauerbrey demonstrated, in 1959, that the frequency change (Δf) of oscillating quartz could be linearly related to its mass change (Δm) as expressed by:

$\Delta f \longleftrightarrow \Delta m$

Δm = -C * 1/n * Δf {where n is the overtone number, and C is a constant that depends on the property of the crystal used. Equation typically referred to as the Sauerbrey equation, constitutes the basic principle of QCM technology. An overtone is any resonant frequency above the fundamental frequency of a sound.}

$\Delta m = -C \frac{1}{n} \Delta f$

$\Delta m = \frac{-C\Delta f}{n}$

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There are two key concepts to keep in mind: the change in frequency (denoted as Δf) and the change in mass (denoted as Δm). The Sauerbrey equation provides a relationship between these two variables. Specifically, it expresses the change in mass (Δm) as proportional to a constant, C. This constant, C, is derived from several parameters, including the density of the quartz, the total added mass, the velocity, and the thickness of the quartz crystal.

The Sauerbrey equation can be expressed as:

$$\Delta m = -C\frac{1}{\mathrm{n}}\Delta f$$

Here, n represents the overtone number, and Δf is the change in frequency. By adjusting the voltage, you can maintain a specific frequency, and if the voltage remains constant, the crystal will continue to vibrate at that unique frequency.

This relationship between mass and frequency is a fundamental aspect of QCM technology, making it an incredibly precise tool for detecting even the slightest changes in mass at the molecular level.

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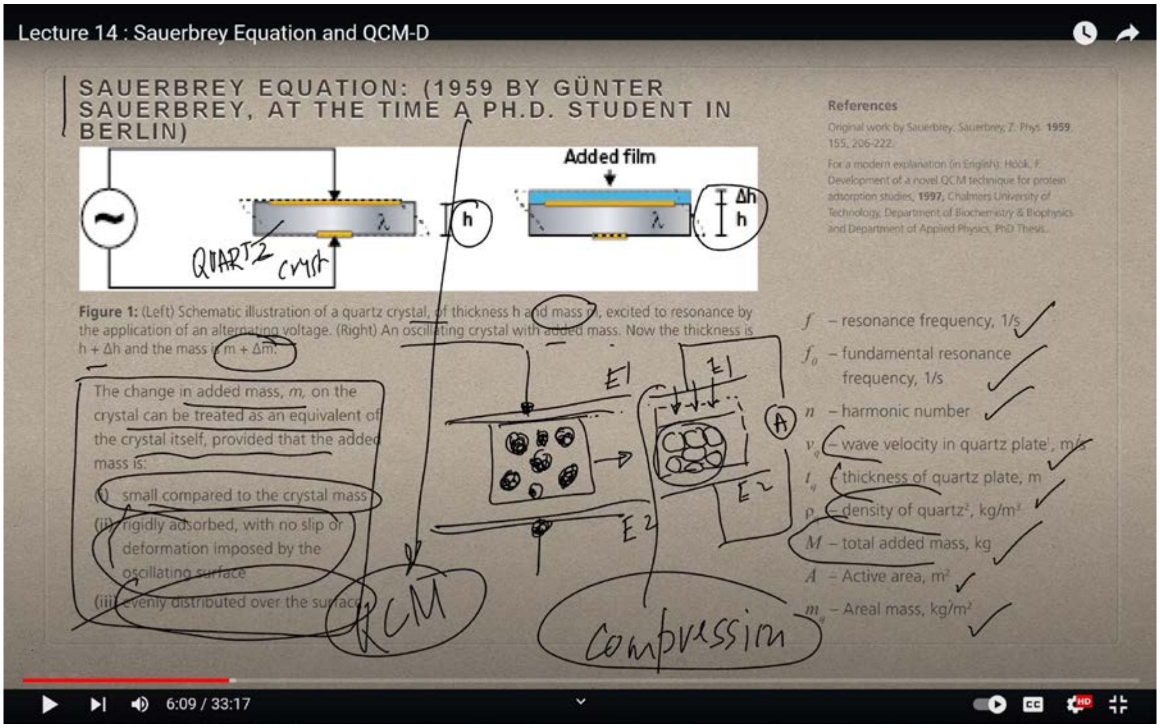

Lecture 14 : Sauerbrey Equation and QCM-D

SAUERBREY EQUATION: (1959 BY GÜNTER SAUERBREY, AT THE TIME A PH.D. STUDENT IN BERLIN)

Figure 1: (Left) Schematic illustration of a quartz crystal, of thickness h and mass m, excited to resonance by the application of an alternating voltage. (Right) An oscillating crystal with added mass. Now the thickness is h + Δh and the mass is m + Δm.

The change in added mass, *m*, on the crystal can be treated as an equivalent of the crystal itself, provided that the added mass is:

(i) small compared to the crystal mass

(ii) rigidly adsorbed, with no slip or deformation imposed by the oscillating surface

(iii) evenly distributed over the surface

References

Original work by Sauerbrey. Sauerbrey, Z. Phys. **1959**, 155, 206-222.

For a modern explanation (in English): Höök, F. Development of a novel QCM technique for protein adsorption studies, **1997**, Chalmers University of Technology, Department of Biochemistry & Biophysics and Department of Applied Physics, PhD Thesis.

f – resonance frequency, 1/s ✓
f_0 – fundamental resonance frequency, 1/s ✓
n – harmonic number ✓
v_q – wave velocity in quartz plate[1], m/s ✓
t_q – thickness of quartz plate, m ✓
ρ_q – density of quartz[2], kg/m³ ✓
M – total added mass, kg ✓
A – Active area, m² ✓
m_q – Areal mass, kg/m² ✓

When you add mass to a system, this change in mass directly affects the frequency. If we examine the relationship described by the equation, it’s almost as if there’s a simple linear connection between the change in frequency and the change in mass. As mass increases, frequency decreases, which appears to be a very straightforward, linear relationship. However, there’s a crucial point to consider regarding where this linear relationship actually applies.

Let’s revisit an earlier slide that I mentioned I’d return to. There are some important details here that I initially didn’t elaborate on. Specifically, the change in added mass M on the crystal can be considered equivalent to the mass of the crystal itself, but only under certain conditions.

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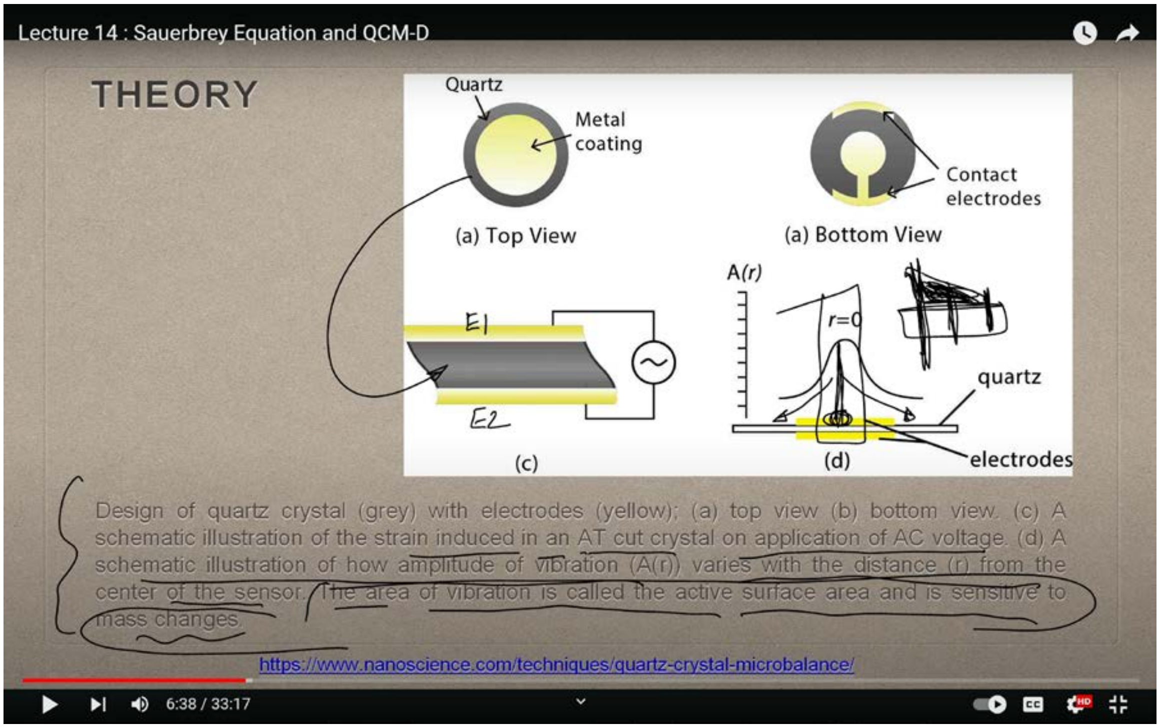

THEORY

Design of quartz crystal (grey) with electrodes (yellow); (a) top view (b) bottom view. (c) A schematic illustration of the strain induced in an AT cut crystal on application of AC voltage. (d) A schematic illustration of how amplitude of vibration (A(r)) varies with the distance (r) from the center of the sensor. The area of vibration is called the active surface area and is sensitive to mass changes.

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These conditions are critical:

1. The added mass must be small in comparison to the crystal mass. For example, if the crystal mass is 1 unit, the added mass should be significantly less, perhaps 0.1 units or less.

Adding a mass comparable to or larger than the crystal itself would disrupt the measurement.

2. The mass must be rigidly adsorbed onto the surface with no slip or deformation caused by the oscillating surface. In other words, once the mass adheres to the surface, it should remain firmly in place. If it behaves like a viscoelastic material, slipping, rolling, or moving around on the surface, the measurement won't be accurate. The mass needs to stay fixed in place rather than shifting or slipping as the surface oscillates.

3. The added mass must be evenly distributed across the surface. Imagine your crystal surface as flat, with a film spread evenly across it. If the film is uneven or clumped, different zones of the crystal will resonate at different frequencies, leading to inaccurate measurements. The mass should adsorb evenly across the surface to maintain the integrity of the measurement.

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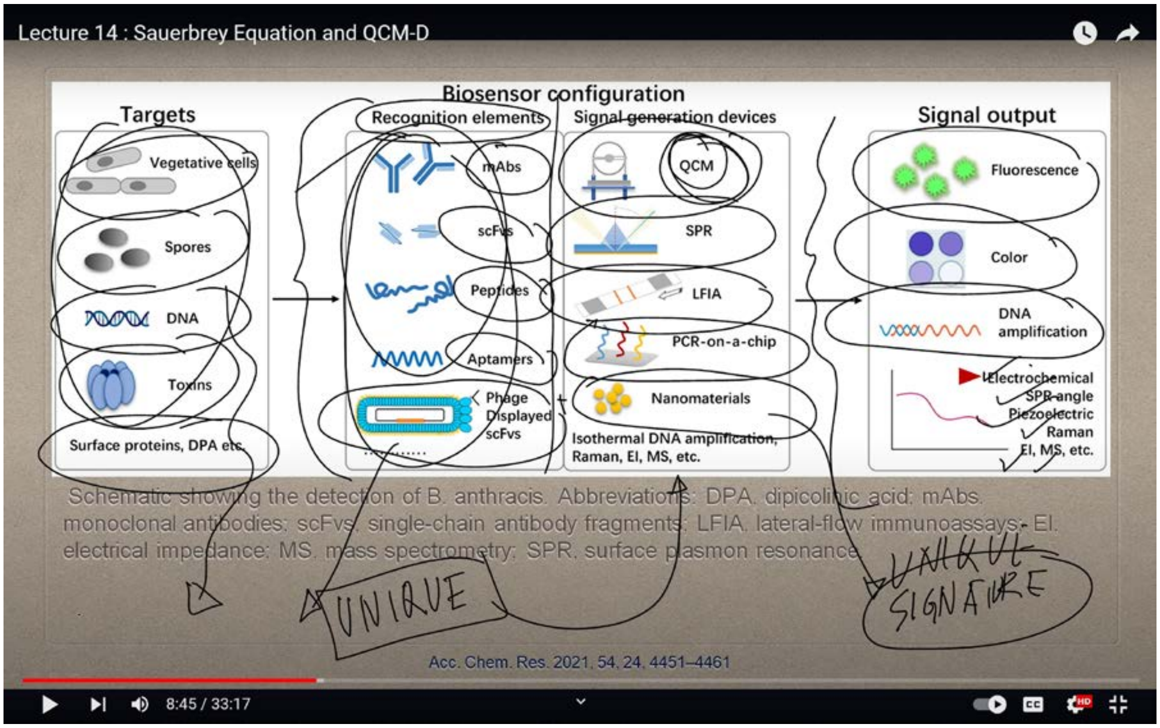

Schematic showing the detection of B. anthracis. Abbreviations: DPA, dipicolinic acid; mAbs, monoclonal antibodies; scFvs, single-chain antibody fragments; LFIA, lateral-flow immunoassays; EI, electrical impedance; MS, mass spectrometry; SPR, surface plasmon resonance.

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Given these conditions, quartz crystal microbalance (QCM) becomes a highly powerful tool for measuring small changes in mass, but only if these requirements are met. Now, let's discuss what the instrumentation for QCM looks like.

The basic setup includes the quartz crystal, held securely in a crystal holder. There’s also an oscillator that generates the frequency, which is measured by a frequency counter. This whole system is connected to a computer, which processes and displays the data. Although this description is highly simplified, it captures the essential components.

However, let's consider a slightly different scenario. When we talk about QCM, we generally assume that everything adheres properly and absorbs correctly. This assumption is crucial for the QCM to function effectively and provide accurate measurements.

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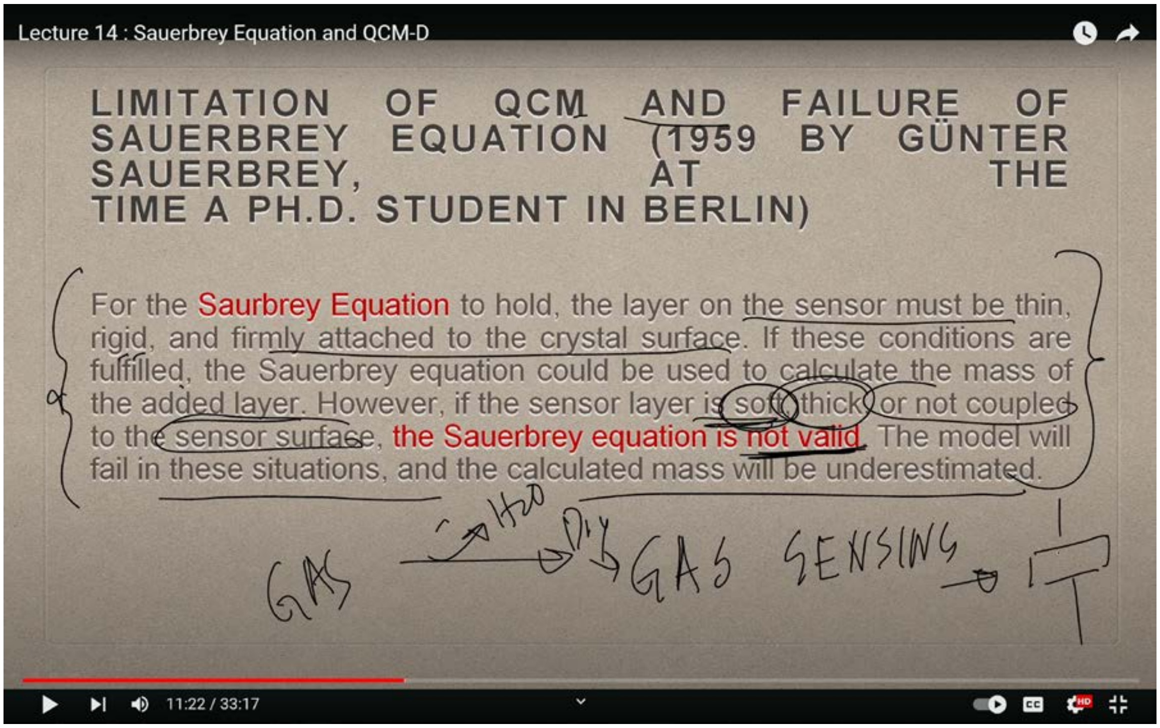

LIMITATION OF QCM AND FAILURE OF SAUERBREY EQUATION (1959 BY GÜNTER SAUERBREY, AT THE TIME A PH.D. STUDENT IN BERLIN)

For the Saurbrey Equation to hold, the layer on the sensor must be thin, rigid, and firmly attached to the crystal surface. If these conditions are fulfilled, the Sauerbrey equation could be used to calculate the mass of the added layer. However, if the sensor layer is soft, thick or not coupled to the sensor surface, the Sauerbrey equation is not valid. The model will fail in these situations, and the calculated mass will be underestimated.

When we talk about adsorption, especially in the context of gas molecules or in dry conditions, it’s relatively straightforward, molecules adhere to a surface in a predictable manner. However, the situation becomes significantly more complex when dealing with the types of molecules we’re interested in, particularly those that don’t remain dry and function optimally in the presence of water. The behavior of these molecules changes drastically when water enters the equation.

For instance, consider a scenario where adsorption occurs in air. Now, imagine the same scenario but with a thin film of water or in a submerged environment. The behavior of the molecules and the resulting frequency changes are not the same. This shift in behavior highlights a critical issue in biosensing, where the molecules we work with often require water to function effectively.

So, the question arises: will Quartz Crystal Microbalance (QCM) still work under these conditions? This brings us to the limitations of QCM and the Sorbet equation. For the Sorbet equation to be applicable, the sensor layer must be thin, rigid, and firmly attached to the crystal surface. However, biological molecules, by their nature, do not conform to these requirements, they are often soft, thick, and not fully coupled to the sensor surface. When these conditions aren’t met, the Sorbet equation fails, leading to an underestimation of the added mass.

These limitations explain why, historically, QCM and the Sorbet equation were primarily used for gas sensing applications. In such cases, you would dry the gas by removing any water, pass it through a chamber, and then measure it on the microbalance. QCM performs exceptionally well in these dry conditions, but it struggles in environments where water and biological molecules are involved.

This brings us to the next level of analysis: what happens in wet conditions, the real-world scenario for biosensors? This is where Quartz Crystal Microbalance with Dissipation (QCM-D) comes into play, with the 'D' standing for dissipation.

Let’s visualize the situation: Imagine a crystal vibrating in the air, it oscillates freely. Now, submerge that crystal in water. Intuitively, you know that its vibration will be dampened due to the film of water around it, restricting its movement.

In a liquid environment, molecular adsorption involves not just the molecules themselves but also associated liquid molecules. These liquid molecules contribute additional dynamic mass through direct hydration, solvation, and entrapment within the adsorbed film, leading to the formation of a soft viscoelastic layer. Picture this: you have the crystal, surrounded by water molecules, with your analyte interacting in this environment. The situation now resembles a viscoelastic film that is not firmly attached to the oscillating crystal.

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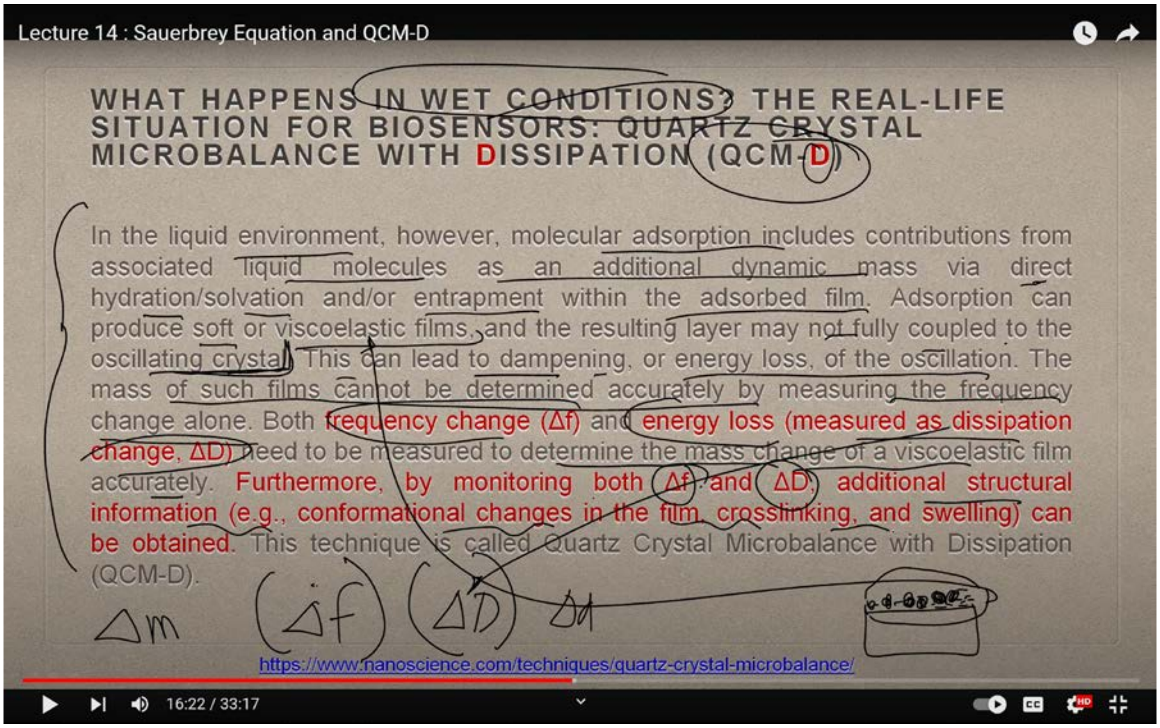

WHAT HAPPENS IN WET CONDITIONS? THE REAL-LIFE SITUATION FOR BIOSENSORS: QUARTZ CRYSTAL MICROBALANCE WITH DISSIPATION (QCM-D)

In the liquid environment, however, molecular adsorption includes contributions from associated liquid molecules as an additional dynamic mass via direct hydration/solvation and/or entrapment within the adsorbed film. Adsorption can produce soft or viscoelastic films, and the resulting layer may not fully coupled to the oscillating crystal. This can lead to dampening, or energy loss, of the oscillation. The mass of such films cannot be determined accurately by measuring the frequency change alone. Both frequency change (Δf) and energy loss (measured as dissipation change, ΔD) need to be measured to determine the mass change of a viscoelastic film accurately. Furthermore, by monitoring both Δf and ΔD, additional structural information (e.g., conformational changes in the film, crosslinking, and swelling) can be obtained. This technique is called Quartz Crystal Microbalance with Dissipation (QCM-D).

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This lack of firm coupling causes energy dissipation or dampening of the oscillation, as the viscoelastic nature of the film leads to slippage and incomplete coupling with the crystal surface. Remember the conditions required for the Sorbet equation to hold: the mass must be rigidly coupled, there should be no slippage, and the mass must be minimal compared to the crystal. In this case, however, these conditions are not met, leading to significant energy loss and dampening of the oscillation.

Imagine pouring a significant amount of water into a system. The oscillation frequency would naturally decrease because the added mass makes the system heavier. Now, if you’re using a sensor that has already absorbed a considerable amount of water, you’ll need to adjust the equation because your baseline frequency has fundamentally changed. The basic theory, which states that the change in mass (Δm) is linearly related to the change in frequency (Δf), no longer applies in this scenario. This is because the frequency now behaves differently due to the dissipation caused by the absorbed water.

In practical terms, consider a dry crystal onto which you place a sample containing antibodies. The water molecules in the sample will adsorb onto the surface, introducing a different type of dampening effect. This means the frequency change will now also reflect this dampening process, leading to energy loss in the oscillation. As a result, the mass of such a film cannot be accurately determined by just measuring the frequency change alone.

Here's where it gets interesting: besides Δf (frequency change), there's another crucial term that comes into play, ΔD, which represents dissipation changes. To accurately determine the mass change of a viscoelastic film, you need to measure both Δf and ΔD. By monitoring these two parameters, you can gain additional insights into the structural properties of the film, such as conformational changes, cross-linking, and swelling.

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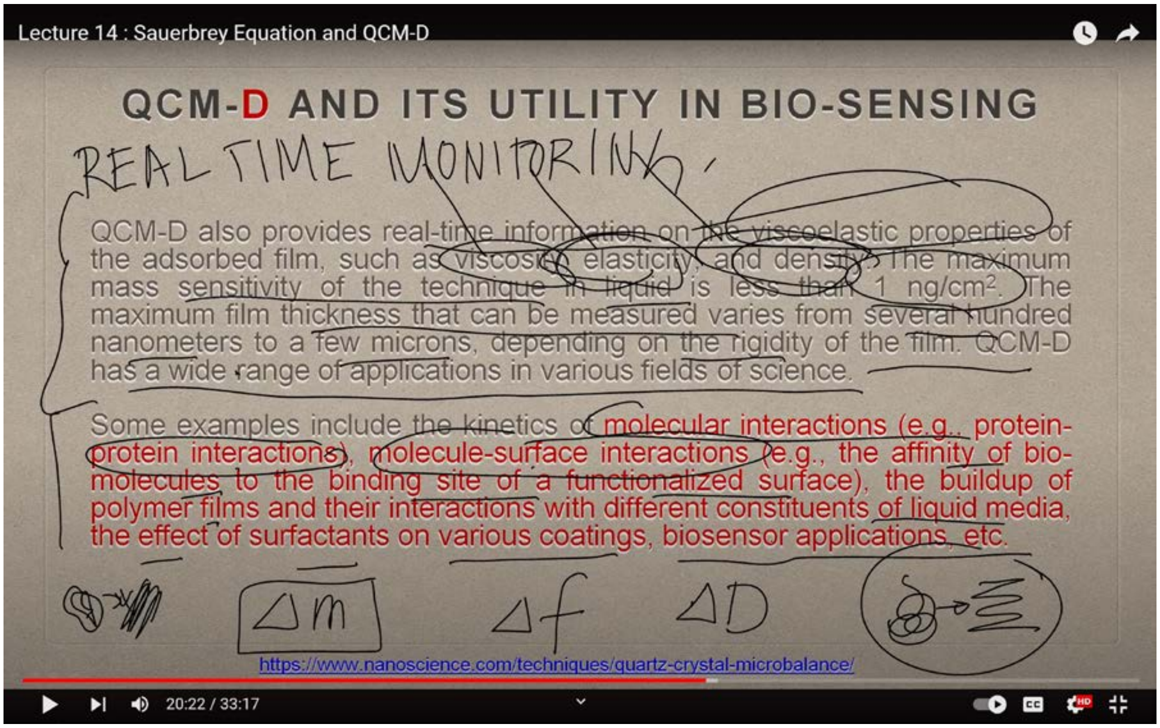

QCM-D AND ITS UTILITY IN BIO-SENSING

REAL TIME MONITORING.

QCM-D also provides real-time information on the viscoelastic properties of the adsorbed film, such as viscosity, elasticity, and density. The maximum mass sensitivity of the technique in liquid is less than 1 ng/cm^2. The maximum film thickness that can be measured varies from several hundred nanometers to a few microns, depending on the rigidity of the film. QCM-D has a wide range of applications in various fields of science.

Some examples include the kinetics of molecular interactions (e.g., protein-protein interactions), molecule-surface interactions (e.g., the affinity of bio-molecules to the binding site of a functionalized surface), the buildup of polymer films and their interactions with different constituents of liquid media, the effect of surfactants on various coatings, biosensor applications, etc.

$\boxed{\Delta m}$ Δf ΔD

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This brings us to the utility of QCM-D (Quartz Crystal Microbalance with Dissipation) in biosensing. QCM-D is not just about measuring mass; it also provides real-time information on the viscoelastic properties of the material, which is particularly relevant for biological molecules and polymers, most of which exhibit viscoelastic behavior. These properties include viscosity (resistance to flow), elasticity, and density.

QCM-D is incredibly sensitive, capable of detecting mass changes as small as less than one nanogram per square centimeter. This is no small feat. Depending on the rigidity of the film, the technique can measure film thicknesses ranging from a few nanometers to several microns.

QCM-D's wide range of applications spans various scientific fields. It's used to study molecular interactions, such as protein-protein interactions and the affinity of biomolecules for binding sites on functionalized surfaces. It's also employed in analyzing the buildup of polymer films, their interactions with different constituents in a liquid medium, and the effects of surfactants on various coatings. In biosensor applications, QCM-D proves to be an exceptionally robust tool.

One of the key strengths of QCM-D is its ability to monitor real-time changes, including protein conformation and molecule-to-surface interactions. For instance, you can observe how a protein's shape changes over time or how two sets of proteins interact. You can also coat a surface with different materials, whether hydrophobic or hydrophilic, and analyze its viscoelastic properties based on viscosity, elasticity, and density.

This is the beauty of QCM-D: it allows for comprehensive monitoring of multiple parameters, providing a deep understanding of the interactions and changes occurring at the molecular level.

You can clearly observe the changes taking place, how much interaction is occurring and the nature of these interactions. The buildup of polymer films, the process of film formation, and whether it results in a continuous layer or not are all aspects that can be monitored. For example, polymers sometimes create a continuous layer, like self-assembled monolayers. Other times, they form fragmented films, and with QCM-D, you can monitor such unique molecular events, which are otherwise challenging to observe with other sensor types.

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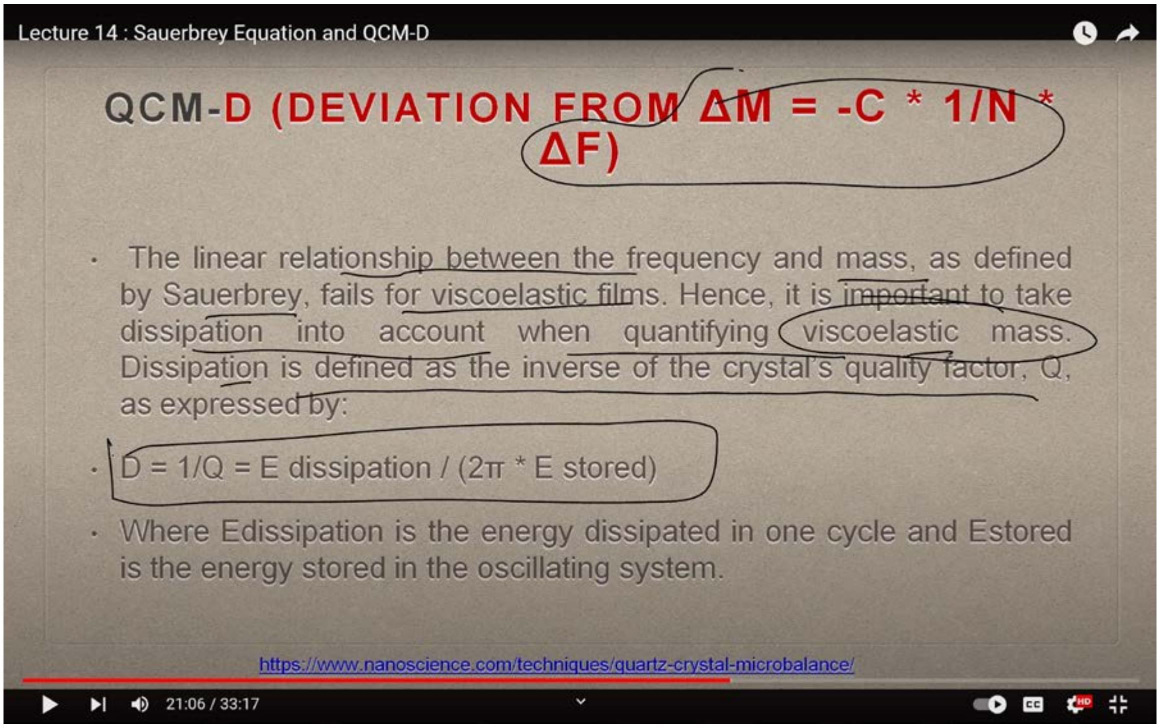

QCM-D (DEVIATION FROM $\Delta M = -C * 1/N * \Delta F$)

- The linear relationship between the frequency and mass, as defined by Sauerbrey, fails for viscoelastic films. Hence, it is important to take dissipation into account when quantifying viscoelastic mass. Dissipation is defined as the inverse of the crystal's quality factor, Q, as expressed by:
- $D = 1/Q = E \text{ dissipation} / (2\pi * E \text{ stored})$
- Where Edissipation is the energy dissipated in one cycle and Estored is the energy stored in the oscillating system.

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Additionally, QCM-D allows you to understand how different liquid mediums can influence the conformational geometry, movement, and self-assembly of molecules. QCM-D deviates from the classic Sorvay equation because the linear relationship between frequency and mass, as defined by Sorvay, does not hold true for viscoelastic films. Therefore, it's crucial to account for dissipation when quantifying viscoelastic mass. Keep in mind the term "viscoelastic mass." Dissipation, in this context, is defined as the inverse of the crystal's quality factor Q, expressed as $D = \frac{1}{Q}$, where $E_{\text{dissipation}}$ is the energy dissipated in one cycle, and E_{stored} is the energy stored in the oscillating system.

There are two primary ways to define QCM-D: using the equivalent circuit model or the mechanical model. When defined by the mechanical model, we focus on the mass. When a piezoelectric quartz crystal resonates, both the electrical current and mass oscillate simultaneously. Consequently, quartz can be represented by either its equivalent electrical circuit or a mechanical circuit.

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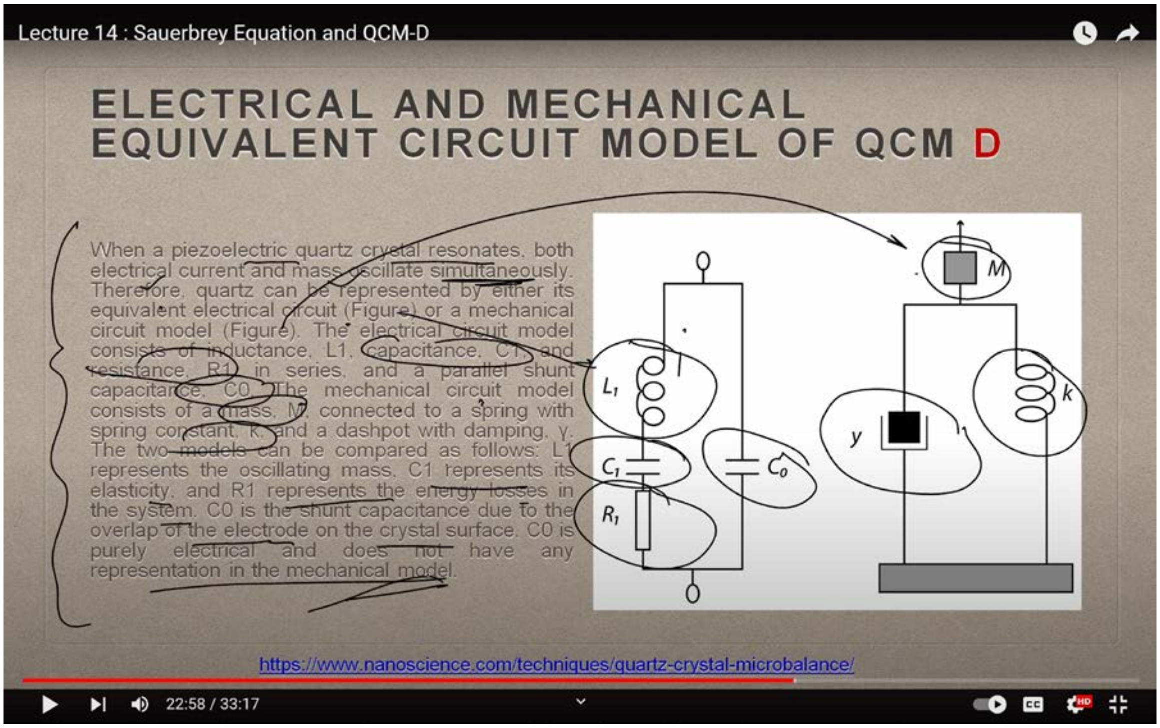

ELECTRICAL AND MECHANICAL EQUIVALENT CIRCUIT MODEL OF QCM D

When a piezoelectric quartz crystal resonates, both electrical current and mass oscillate simultaneously. Therefore, quartz can be represented by either its equivalent electrical circuit (Figure) or a mechanical circuit model (Figure). The electrical circuit model consists of inductance, L1, capacitance, C1, and resistance, R1 in series, and a parallel shunt capacitance, C0. The mechanical circuit model consists of a mass, M, connected to a spring with spring constant, K, and a dashpot with damping, γ. The two models can be compared as follows: L1 represents the oscillating mass, C1 represents its elasticity, and R1 represents the energy losses in the system. C0 is the shunt capacitance due to the overlap of the electrode on the crystal surface. C0 is purely electrical and does not have any representation in the mechanical model.

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The electrical circuit model comprises an inductance (L), capacitance (C), and resistance (R) in series, with a parallel shunt resistance. The mechanical circuit model includes mass (m), connected to a spring with a constant (k) and a dashpot with a damping coefficient (y). The components of these models can be compared as follows: L_1 represents the oscillating mass, C_1 represents elasticity, and R_1 accounts for energy loss in the system. The shunt capacitance C_0 arises from the electrode overlap on the crystal surface and is purely electrical, with no mechanical counterpart.

When analyzing energy dissipation using the electrical circuit model, it is defined as $D = \frac{1}{Q} = \frac{R1}{2\pi f}$, where f is the frequency. The two most common approaches to measuring energy dissipation using the electrical circuit model are resistance analysis and impedance analysis, with a third, more recent technique also in use. In resistance analysis, the resistance of the crystal is measured by introducing a small resistor into the circuit and observing the voltage change. The current in the equivalent circuit of the resonating crystal, after canceling out the shunt capacitance C_0, will be proportional to the crystal's resistance R_1, which sums up the losses. However, this approach does not provide an absolute value because the inductance L_1 is unknown in this measurement. Moreover, achieving valid cancellation of C_0 can be problematic if the crystal is significantly loaded, making resistance analysis useful for obtaining relative structural data rather than absolute values.

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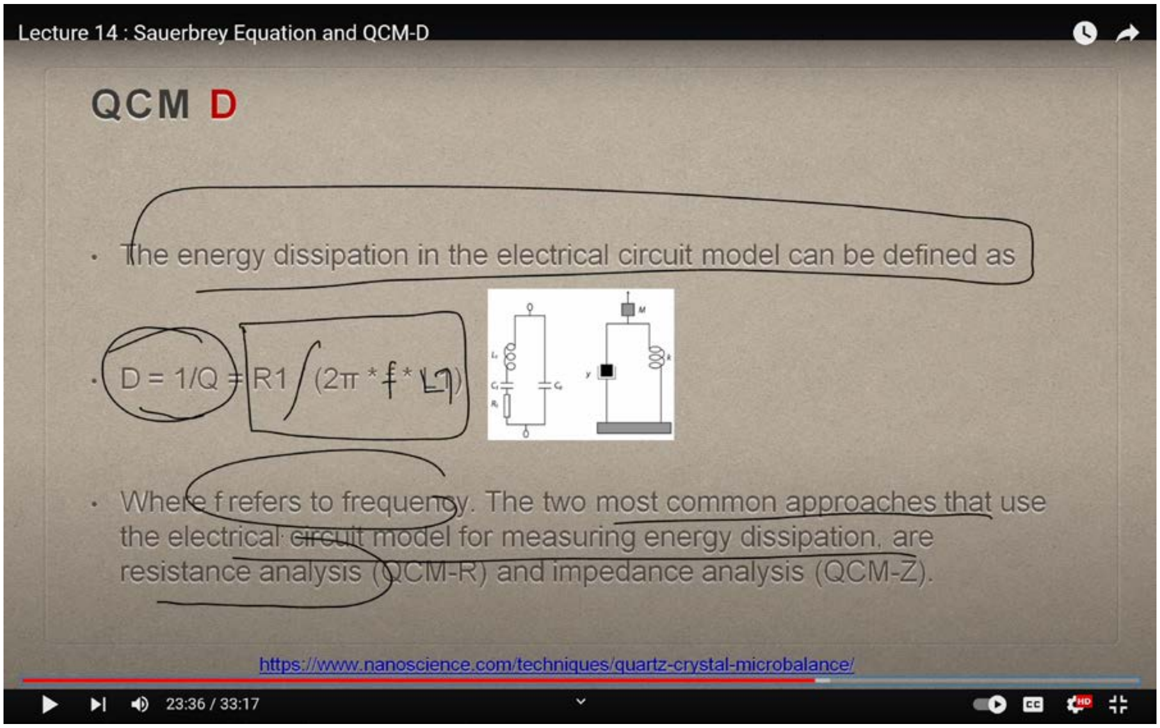

QCM **D**

- The energy dissipation in the electrical circuit model can be defined as
- $D = 1/Q = R1 / (2\pi * f * L1)$
- Where f refers to frequency. The two most common approaches that use the electrical circuit model for measuring energy dissipation, are resistance analysis (QCM-R) and impedance analysis (QCM-Z).

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You don't obtain unique absolute data from this method, but impedance analysis offers a more refined approach. In impedance analysis, QCM-Z provides a well-defined method for measuring energy loss. This technique allows you to determine all four elements of the crystal's equivalent circuit: L_1, C_1, R_1, and the shunt resistance. Here's how it works.

First, you have an equivalent circuit setup that includes a frequency generator, which supplies varying input frequencies to the circuit. At each sweep frequency, both the current and phase are recorded, enabling all four components, L_1, C_1, R_1, and the shunt, to be numerically fitted. However, there's a limitation: this fitting process is only effective when the crystal is in a steady state. The crystal must stabilize at each frequency step, making data generation extremely time-consuming. This is one of the drawbacks of the impedance analysis QCM-Z process.

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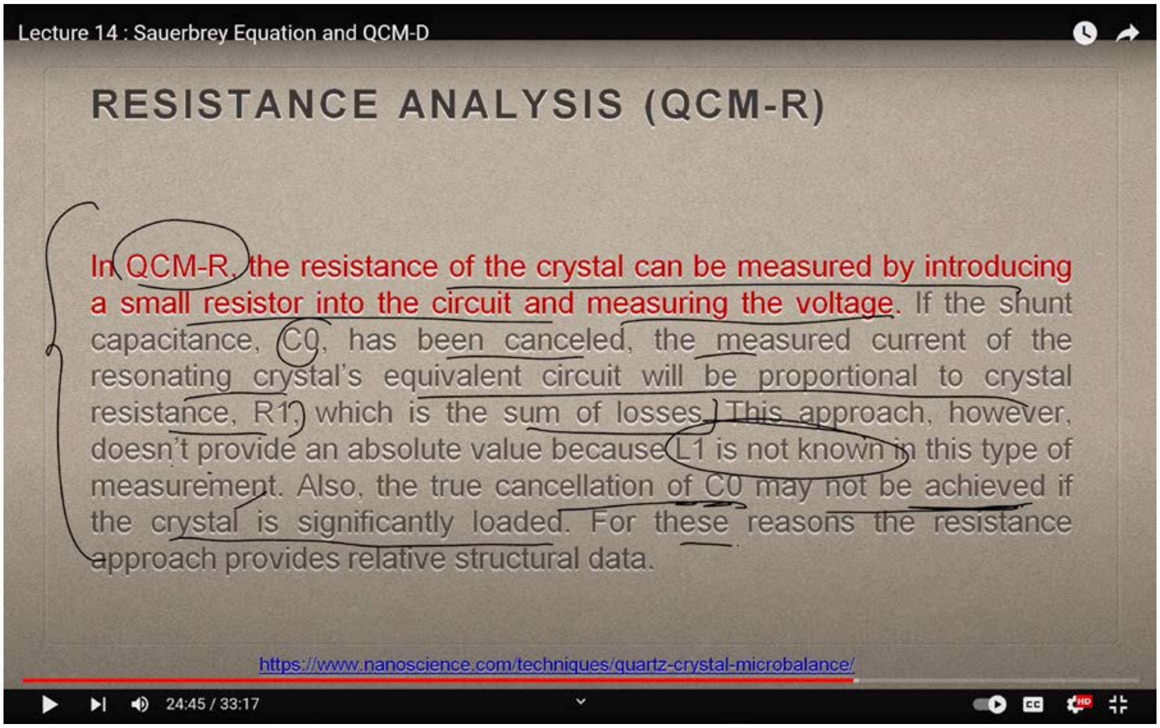

RESISTANCE ANALYSIS (QCM-R)

In QCM-R, the resistance of the crystal can be measured by introducing a small resistor into the circuit and measuring the voltage. If the shunt capacitance, C0, has been canceled, the measured current of the resonating crystal's equivalent circuit will be proportional to crystal resistance, R1, which is the sum of losses. This approach, however, doesn't provide an absolute value because L1 is not known in this type of measurement. Also, the true cancellation of C0 may not be achieved if the crystal is significantly loaded. For these reasons the resistance approach provides relative structural data.

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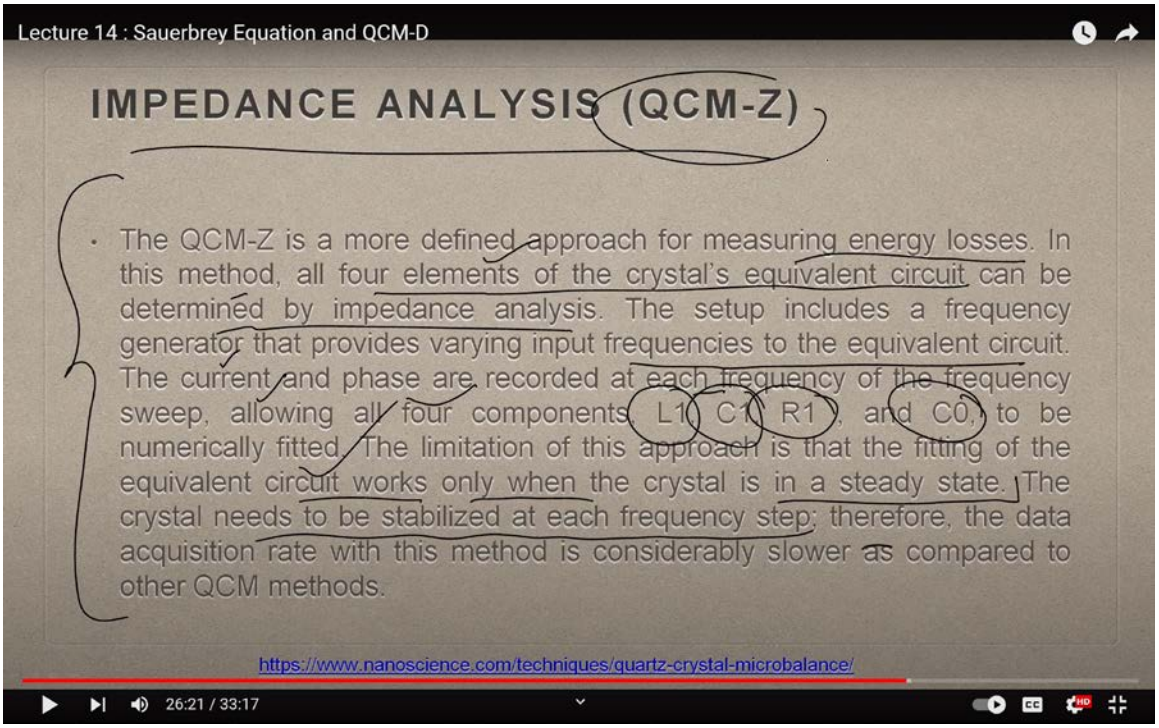

IMPEDANCE ANALYSIS (QCM-Z)

- The QCM-Z is a more defined approach for measuring energy losses. In this method, all four elements of the crystal's equivalent circuit can be determined by impedance analysis. The setup includes a frequency generator that provides varying input frequencies to the equivalent circuit. The current and phase are recorded at each frequency of the frequency sweep, allowing all four components L1, C1, R1, and C0, to be numerically fitted. The limitation of this approach is that the fitting of the equivalent circuit works only when the crystal is in a steady state. The crystal needs to be stabilized at each frequency step; therefore, the data acquisition rate with this method is considerably slower as compared to other QCM methods.

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I also mentioned a fourth method that is rapidly gaining popularity: Quartz Crystal Microbalance with Energy Dissipation, or QCM-D. In this technique, the quartz crystal is briefly excited to its resonant frequency by applying a driving voltage across it. The crystal, along with the electrode, resonates for a short period, and then the driving voltage is turned off. Afterward, the decay of the voltage over the crystal is recorded as a function of time.

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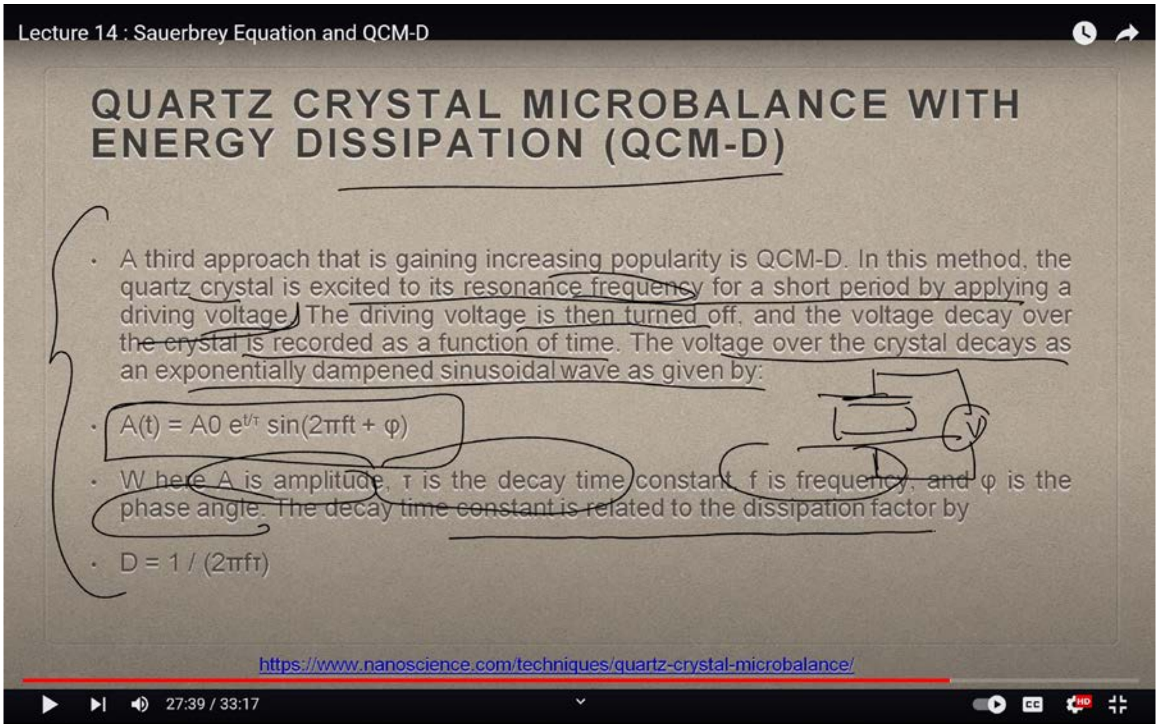

QUARTZ CRYSTAL MICROBALANCE WITH ENERGY DISSIPATION (QCM-D)

- A third approach that is gaining increasing popularity is QCM-D. In this method, the quartz crystal is excited to its resonance frequency for a short period by applying a driving voltage. The driving voltage is then turned off, and the voltage decay over the crystal is recorded as a function of time. The voltage over the crystal decays as an exponentially dampened sinusoidal wave as given by:
- $A(t) = A0\ e^{t/\tau} \sin(2\pi ft + \varphi)$
- W here A is amplitude, τ is the decay time constant, f is frequency, and φ is the phase angle. The decay time constant is related to the dissipation factor by
- $D = 1 / (2\pi f\tau)$

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The voltage decay over the crystal follows an exponentially dampened sinusoidal pattern, described by a specific mathematical expression where A is the amplitude, τ is the decay time constant, f is the frequency, and θ is the phase angle. The decay time constant τ is directly related to the dissipation factor, making this method highly effective.

By numerically fitting the decay curve, you can simultaneously obtain both the frequency and dissipation of the crystal. The decay time constant provides insights into the rigidity or softness of the mass adsorbed on the crystal surface. For instance, in rigid materials like metal films that couple well with the oscillating quartz, the decay of oscillation is slower, resulting in a longer decay curve.

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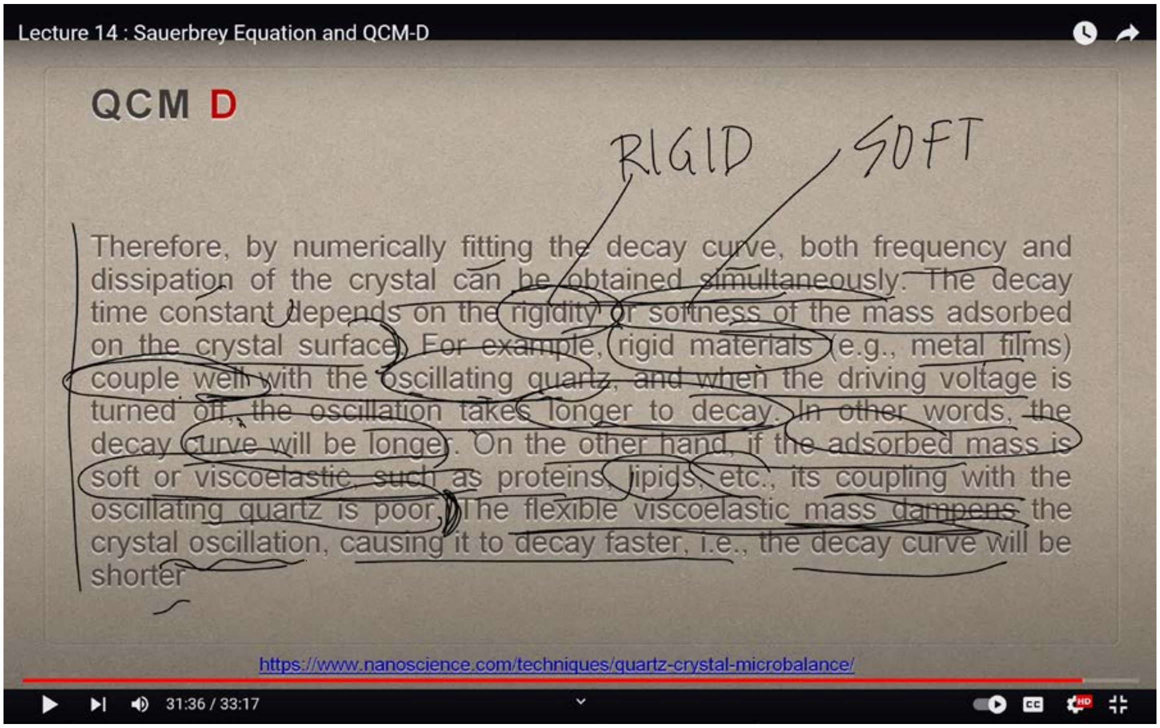

QCM D

Therefore, by numerically fitting the decay curve, both frequency and dissipation of the crystal can be obtained simultaneously. The decay time constant depends on the rigidity or softness of the mass adsorbed on the crystal surface. For example, rigid materials (e.g., metal films) couple well with the oscillating quartz, and when the driving voltage is turned off, the oscillation takes longer to decay. In other words, the decay curve will be longer. On the other hand, if the adsorbed mass is soft or viscoelastic, such as proteins, lipids, etc., its coupling with the oscillating quartz is poor. The flexible viscoelastic mass dampens the crystal oscillation, causing it to decay faster, i.e., the decay curve will be shorter

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Conversely, if the adsorbed mass is soft or viscoelastic, such as proteins or lipids, the coupling with the quartz is weaker, leading to faster decay and a shorter decay curve.

To help you understand, here's a schematic of the decay curve. Notice how the curve behaves differently based on the material's properties. Before the material interacts with the surface, the decay curve behaves a certain way. But once the material, especially viscoelastic substances, engages, the curve changes significantly. For example, rigid materials like metal films couple effectively with oscillating quartz, resulting in a more extended decay, as described in this increasingly popular QCM-D approach.

In this method, the quartz crystal is initially excited to its resonant frequency. If you observe the process closely, you'll notice that the crystal begins oscillating at this resonant frequency, which is key to the analysis. Now, the main objective here is to monitor how this resonance frequency changes over time.

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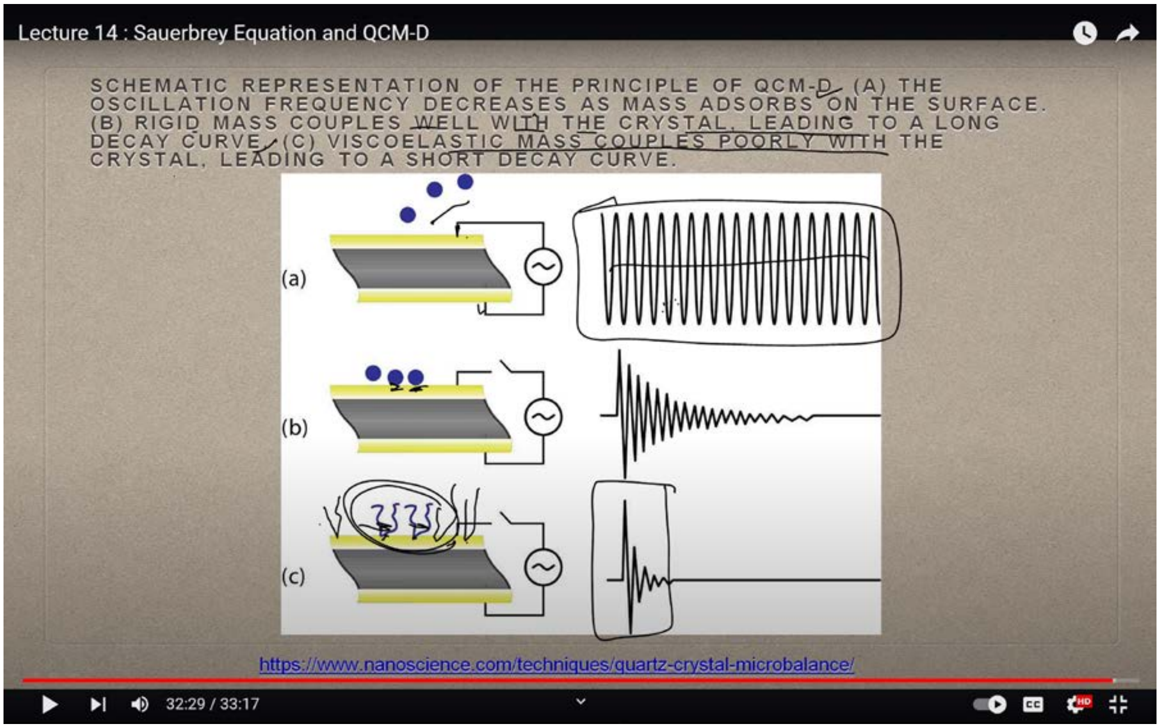

SCHEMATIC REPRESENTATION OF THE PRINCIPLE OF QCM-D. (A) THE OSCILLATION FREQUENCY DECREASES AS MASS ADSORBS ON THE SURFACE. (B) RIGID MASS COUPLES WELL WITH THE CRYSTAL, LEADING TO A LONG DECAY CURVE. (C) VISCOELASTIC MASS COUPLES POORLY WITH THE CRYSTAL, LEADING TO A SHORT DECAY CURVE.

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Here's how it works: You start by applying a driving voltage across the crystal, which induces the resonance. Once the crystal is resonating, the driving voltage is then switched off. Even after the voltage is cut off, the crystal continues to resonate for a brief period. During this time, the decay of the voltage across the crystal is recorded as a function of time, which allows you to measure how quickly the resonance diminishes.

The voltage decay follows an exponentially dampened sinusoidal wave, a pattern described by specific mathematical expressions. By numerically fitting the decay curve, you can simultaneously determine both the frequency and dissipation of the crystal.

It's important to note that the decay time constant is a crucial factor here, as it depends on the rigidity or softness of the mass adsorbed on the crystal surface. For instance, if the adsorbed material is rigid, such as a metal film, it couples well with the oscillating quartz. As a result, when the driving voltage is turned off, the oscillation takes longer to decay, resulting in a longer decay curve.

On the other hand, if the adsorbed mass is soft or viscoelastic, such as proteins, lipids, or other biological molecules, it doesn’t couple as effectively with the quartz. This poor coupling leads to faster damping of the crystal oscillation, resulting in a shorter decay curve.

To help visualize this, consider a schematic where the mass contacts the surface. In cases where surface contact is minimal, the materials slip over the surface, leading to faster damping. Conversely, better surface contact results in slower damping. This schematic representation illustrates the principle of QCM-D: as mass adsorbs onto the crystal surface, the oscillation frequency decreases. Rigid masses lead to longer decay curves due to effective coupling, while viscoelastic masses result in shorter decay curves due to poor coupling. These are the fundamental concepts behind understanding how QCM-D works. Thank you.